

UNCLASSIFIED

Defense Technical Information Center
Compilation Part Notice

ADP010887

TITLE: Convoy Planning in a Digitized Battlespace

DISTRIBUTION: Approved for public release, distribution unlimited

This paper is part of the following report:

TITLE: New Information Processing Techniques for
Military Systems [les Nouvelles techniques de
traitement de l'information pour les systemes
militaires]

To order the complete compilation report, use: ADA391919

The component part is provided here to allow users access to individually authored sections of proceedings, annals, symposia, ect. However, the component should be considered within the context of the overall compilation report and not as a stand-alone technical report.

The following component part numbers comprise the compilation report:

ADP010865 thru ADP010894

UNCLASSIFIED

Convoy Planning in a Digitized Battlespace

S. A. Harrison

Pattern and Information Processing
Defence Evaluation and Research Agency (DERA)
St. Andrews Road
Great Malvern
Worcestershire WR14 3PS
UK

tel.: +44 (0)1684 895686

fax.: +44 (0)1684 894384

email: SAHARRISON@DERA.GOV.UK

Summary: In this paper we present a formal specification of a convoy planning problem in terms of a time-space network. We apply advanced heuristic techniques to this model and evaluate the approach on a number of realistic scenarios based on the UK MoD's Scenario Advisory Group (SAG) settings. The results demonstrate that the method described is an effective approach for solving practical instances of convoy planning. We also describe an automated planning tool that has been developed, based on the techniques described in this paper and which has been used to plan simulated movements of realistic size. The tool runs on a laptop, is fast and reduces planning time from man-hours to a few seconds.

The value of the techniques described in this paper is not limited to this one application. Hence, we review a representative set of military applications where we expect these techniques to be equally beneficial.

1 Introduction

Moving men and materials in large numbers and quantities is a long-standing military problem faced by all arms. For land forces in particular, present-day military engagements emphasize the need for mobility more than ever. Thus, routing convoys so that they reach their correct destinations in the shortest time is important. But the planning task itself can be considerable, and must be carried out quickly if the tempo of operations is to be maintained. With this requirement in mind, we have examined the development of a planning tool to assist in the strategic routing of objects between specific origin-destination pairs, taking into account the

sorts of restrictions that are likely to be met in practice. The planning tool is suitable for running on a laptop computer and is based on an optimisation formulation.

There are many real-world applications for which a similar approach to the one described in this paper could be adopted directly - for example, moving forces into a remote operational theatre, strategic-level routing of hazardous materials through a given route network, or the routing and scheduling of trains over a rail network.

Not surprisingly, there is an optimisation problem at the heart of many military decision processes. A detailed discussion of the construction of optimisation models from military applications, and methods used to solve them, are given in [15].

1.1 Document overview

In this paper, we develop a model for the convoy routing, based on an optimisation formulation that exploits the concept of a time-space network. We apply a Lagrangian relaxation to this model and show that the resulting Lagrangian dual function may be evaluated efficiently using an enhanced version of Dijkstra's shortest path algorithm that is applicable to very large, implicitly-defined graphs - see [10, 11, 12].

The remainder of the paper is structured as follows. In the next section, we provide some background and in section 3 we outline the benefits of an optimisation based approach to military planning. Then in section 4 we present a formal specification of the convoy routing problem. In section 5, we describe the time-

© British Crown Copyright 2000/DERA.

Printed with the permission of the controller of Her Britannic Majesty's Stationery Office.

space network model for the convoy routing problem and in section 6, we describe a Lagrangian relaxation of the time-space model and discuss how the algorithm is implemented. In section 7 we describe a planning tool based on the techniques described in this paper and its application to some realistic scenarios. Section 8 discusses the effect of uncertainties, such as on route delays and third party disruptions, on the implementation of the plans obtained and how we can account for these uncertainties in the planning process. A number of other applications where we expect the methods described in this report to be beneficial are discussed in section 9. We finish with conclusions.

For a detailed technical discussion of the methods described in this paper the interested reader is referred to [1].

2 Background

In this paper we consider a strategic network routing problem which is applicable to situations where certain objects, or commodities, are to be shipped, or transported, between specified origin-destination pairs with restrictions on how objects may encounter each other en route. The problem we consider is motivated by, and is presented in terms of, an application in which the objects are military convoys. For this reason, we have christened our problem the **convoy movement problem**, or **CMP** for short. There are many real-world applications for which a similar approach could be adopted. For example, the deployment of a force into a remote operational theatre; strategic level routing of hazardous materials through a given route network [7]; or the routing and scheduling of trains over a rail network [2, 3, 8] could easily give rise to instances of the CMP.

Modern military doctrine places great emphasis on the generation of a fast level of operational tempo. The movement of one's own forces into their correct locations is regarded as a key function, the planning of which needs to be completed quickly if the tempo of operations is to be maintained. In the recent action in the Balkans, for example, an enormous amount of time will have been spent on detailed planning for the movement of convoys in Kosovo. More generally, such planning could be further complicated by the fact that the enemy will be attempting to disrupt one's own actions through the disruption or destruction of the road network. The aim of the work reported in this paper is to reduce the amount of time required for the planning process. It is intended to incorporate the algorithms resulting from this

research into the British Army Digitisation Programme. This programme aims to enhance the operational effectiveness of UK forces in joint and combined operations by using modern information technology to couple weapons, sensors, communications and information systems (CIS) across the battlespace and thus create an effective, robust, efficient and affordable federation of systems.

3 Military Benefits of Optimisation

At the heart of many aspects of the military decision process are constrained optimisation problems. Finding the optimal set of resources required to achieve a set of targets subject to restrictions (or constraints) on the possible alternatives is typical of the problems that military commanders are required to solve and that can be formulated as constrained optimisation problems.

Traditional optimisation approaches, such as branch-and-bound, rely upon linear methods that are unable to handle the full complexity of real-world problems effectively. Moreover, traditional methods do not allow for rapid re-planning or the investigation of "what if" scenarios in a timely manner.

In contrast, heuristic based optimisation techniques provide the capability for planning in real world applications with their associated complexities and uncertainties. Plans obtained from approaches based on heuristic based optimisation techniques are generally of high quality and rapidly obtained.

An approach based on formulating aspects of the decision making process as an optimisation problem and employing heuristics to obtain near optimal solutions rapidly leads to the development of automated decision making tools. The benefits of such automation include

- an increase in the speed of processing data,
- reduction in the workload and stress of staffs freeing them for other roles and functions;
- stable performance, of military staffs, with time as opposed to the unavoidable degradation of human performance with fatigue and stress; and
- the ability to cope with the highly complex scenarios associated with the modern battlespace with a greater level of accuracy and effectiveness.

All of which leads to an increase in the speed and tempo of operations, which in turn enables the commander to get inside the opposing forces decision making cycle.

4 Convoy Planning

In this section, we present a formal specification of the CMP. This is a slightly modified version of the specification given in Lee, McKeown and Rayward-Smith [9].

In a CMP, we are given a collection of military units (**convoys**). Each convoy consists of a collection of vehicles that must travel nose to tail in a pre-specified order with pairs of vehicles maintaining a spacing of between fifty and hundred metres. Associated with each convoy are an **origin** and a **destination** such that the convoy must move from the origin to the destination location across a limited route network. The objective is to find a set of paths (or a **movement**) such that the total movement cost for all of the convoys is minimised, where the movement cost is defined to be the summed completion times of all the convoys.

Different types of convoys are composed of different numbers and types of vehicles. Hence they may move at different speeds along the same parts of the network. Indeed, some types of convoy may not be able to use some parts of the network at all. Furthermore, a convoy of a given type may travel at a different speed when moving in one direction along part of the network from when moving in the opposite direction. For example, consider a convoy going up an incline and the same convoy going down the same incline. Further, a given type of convoy may be able to travel in one direction along some parts of the network, but not in the opposite direction. In this paper, we assume convoys are not allowed to stop en-route.

We define the route network in terms of a set of nodes, one per junction in the underlying road network, and a set of links. A link is defined between a pair of nodes if the corresponding junctions in the underlying road network are joined by a road that does not go through any other junctions en-route. Associated with each link and each convoy pairing is a cost. The cost denotes the number of time units required by the convoy to travel directly between the underlying junctions. The cost is either a positive, non-zero integer or ∞ . If the cost is ∞ the convoy cannot travel along the underlying road. The cost, for some convoys, in one direction along a link is not necessarily equal to the cost, for the same convoy, in the opposite direction. An example route network is shown in Figure 1.

A **movement** consists of a set of paths across the route network, one per convoy. Paths followed by different convoys may use common parts of the route network but two convoys cannot occupy the same part of the route network at the same time. When two convoys attempt to use the same part of the route network simultaneously this is referred to as a **conflict**.

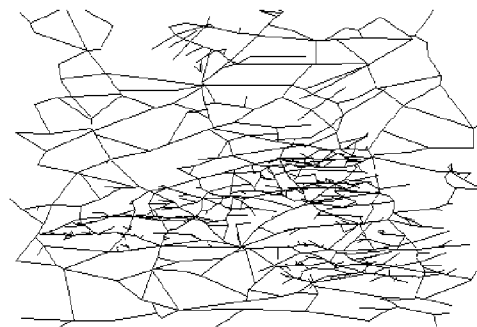


Figure 1: Example of a route network.

Associated with each convoy is a **time-window**. The time window is the time it takes for a convoy to pass through any point in the route network, although it can be interpreted as the time during which the convoy blocks a node in the route network. When a convoy is blocking a node no other convoy may enter the node. The time window represents the convoy's length.

In practice the time taken by a convoy to pass through a particular point in the route network will depend on the point and on the time when the point is reached. However, detailed knowledge of this nature for all points in the route network is unlikely to be available a priori, and in any case may be of a non-deterministic nature. Thus, for an approach to be of practical interest, it is essential to introduce a *simple* device that enables the user to adapt the convoy planning to varying circumstances. This is the purpose of the safety time-window, the value of which could be increased or decreased depending on the planner's confidence in the available data (intelligence). In particular, the size of the time-window will often be an over-estimate.

We also associate with each convoy an **earliest ready time**. This is the earliest time at which a convoy can start its movement and represents constraints imposed by earlier phases of an operation. The convoy does not have to start its movement at its earliest ready time. It can delay its movement as this will often allow the convoy to follow a quicker route whilst avoiding later conflicts. The **initial delay** on a particular convoy's movement is a variable whose value is to be determined during the planning process. A zero delay corresponds to a convoy starting its

motion at its earliest ready time. For simplicity we assume that a convoy's initial delay must be an integer multiple of some prescribed **waiting interval**. The waiting intervals may be of different durations for different origins and different convoys.

Hence, a movement consists of a set of paths and a set of initial delays, one path and one delay for each convoy. We refer to the pairing of a path and an initial delay as the **route**. The **completion time** of a particular convoy's route is then the convoy's earliest start time plus its initial delay plus the time it takes for the convoy to traverse its path plus the convoy's time-window. Including the convoy's time-window accounts for the time required to allow the entire body of the convoy to arrive at and enter the destination. We refer to the collection of all the routes as the **movement**. The **overall completion time** is then just the sum of the completion time for all the routes in the movement.

We also associate with each convoy a **finish time** (or deadline). A movement is said to be valid (or **feasible**) if there are no conflicts and each convoy's completion time is less than its finish time, that is, every convoy has met its deadline.

Therefore, the aim is to find a valid movement such that the overall completion time of the movement is **minimal** with respect to all the valid movements; that is, there is no valid movement with a shorter overall completion time.

5 Time-Space Networks

In this section, we present a model of the CMP in which we relax the constraints associated with conflict prevention. The constraints associated with conflict prevention are **complicating constraints**; that is, if these constraints are removed the resultant optimisation problem is relatively straightforward to solve.

We introduce the concept of a **time space network** in terms of a single convoy. The route, associated with the convoy, is represented on the vertical axis by distance along the route and time is indicated on the horizontal axis. The convoy's occupancy of the route, in time and space, is indicated by a skewed rectangle - as illustrated in Figure 2. We refer to the skewed rectangle as the convoy's **time space occupancy**.

As the source and destination points of the route cannot be changed, nor in this simple example can the route, then the only freedom available to schedule the convoy is the initial delay.

Changing the initial delay corresponds to sliding the convoy's time space occupancy horizontally between the vertical lines that indicate the earliest ready time and the finish time. Clearly for the route to be valid with respect to the earliest ready time and the finish time the convoy's time space occupancy must lie entirely between these two limits.

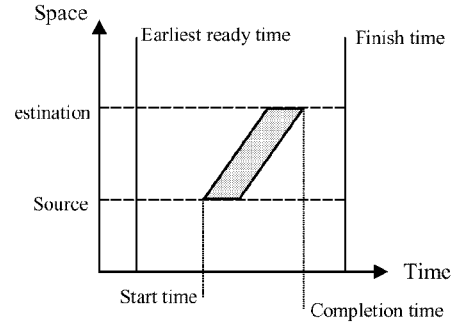


Figure 2: The time-space network.

The **time-space network** formulation is extended to multiple convoys and a route network as follows. First we define a **time frame**, for example, from the minimum earliest ready time to the maximum finish time over all the convoys, and we discretise the interval in some manner.

For each node in the route network and each time step in the discretised time frame we define a time-expanded copy of the node. For each link in the route network and each time-expanded copy of the head node we define a time-expanded copy of the link. We also add in additional links out of each origin node to model initial delays. We refer to resulting set of time-expanded nodes and links as the time-space network (associated with an instance of CMP).

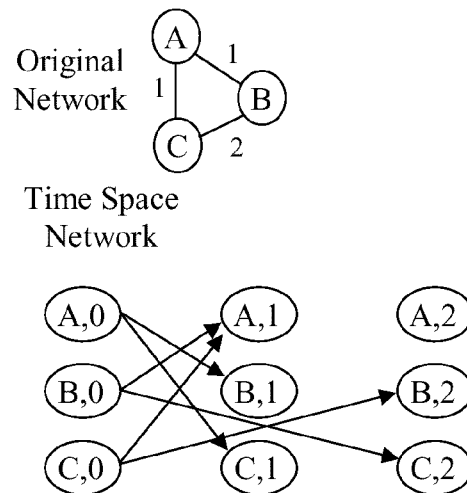


Figure 3: A time-space network

An illustration of a simple route network and an associated time space network is shown in Figure 3. The time space network is only expanded over the first few time steps to avoid an overly complex figure. The same structure of inter-connections will be repeated throughout the entire time space network unless links in the underlying network have time dependent costs.

It is easily seen that a path across the time space network from an origin node at the start of the time frame corresponds to a route. While it would be convenient if a set of disjoint paths on the time-space network defined a valid movement this is not quite the case. However, within the implementation we are able to straightforwardly generate sets of paths across the time-space network that correspond to valid movements.

The size of the resultant time-space network is a function of the number of convoys; the size of the route network; the size of the time frame and the granularity at which the planning is done. For realistic problems with hundreds (or thousands) of convoys; thousands of nodes; time frames stretching over tens of hours and movements planned down to the granularity of minutes the time-space network can easily become very large. Hence it is often impractical to store the network explicitly. In order to handle these very large time space networks in practice, the time-space network must be stored implicitly requiring an efficient implementation with sophisticated memory management techniques.

6 Relaxation Based Optimisation

As we have already stated if we were able to ignore the complicating constraints, that is, those associated with conflict prevention, the problem could be solved straightforwardly, by repeated application of Dijkstra's shortest path algorithm. However, we cannot ignore these constraints. Instead we can relax the constraints through a Lagrangian relaxation formulation of the problem.

Since the seminal work of Held and Karp [6], **Lagrangian relaxation** has enjoyed considerable success for solving combinatorial optimisation problems with large numbers of constraints. This heuristic techniques provides a framework for handling constraints whose presence complicates a mathematical programme the solution of which would otherwise be fairly straightforward. The essential idea of the approach is to price out the complicating constraints, in a systematic manner, using **Lagrange multipliers**. In this way, a Lagrangian **dual problem** is defined

corresponding to a given optimisation problem (referred to as the **primal problem**). Assuming the primal problem is a minimisation problem, to solve the Lagrangian dual problem we must maximise the corresponding Lagrangian dual function. Typically, this is done using a **subgradient optimisation** procedure [14].

The maximised dual function provides a **lower bound** on the minimal solution to the primal problem, that is, a value that is guaranteed to be no greater than the minimal solution's value. In general, the lower bound is close to the minimal value in which case it is said to be **tight**. Given the dual solution, corresponding to the maximised dual function, we can use the dual solution to heuristically construct a solution to the primal problem. The constructed solution is usually of high quality, where high quality corresponds to a small objective function value. If we compare the quality of the primal solution with the lower bound we have a bound on the quality of the primal solution with respect to the minimal solution. Often the quality of the resultant primal solution is found to be within a few percent of the minimal.

In the context of the CMP the complicating constraints are those associated with the conflict prevention. If we were to relax these constraints and allow conflicts the resulting problem could be solved by the repeated application of Dijkstra's shortest path algorithm to generate the shortest path for each convoy between origin and destination. We could then route each convoy along its shortest path starting at its earliest ready time. Clearly the overall completion time for this movement is a lower bound as no faster movement can exist. In general, this movement is not valid and the lower bound is not very tight. We refer to this as the *shortest paths* movement.

We define our Lagrangian dual function by pricing out the constraints associated with conflict prevention. To illustrate how we are able to price out the constraints associated with conflict prevention consider Figure 4.

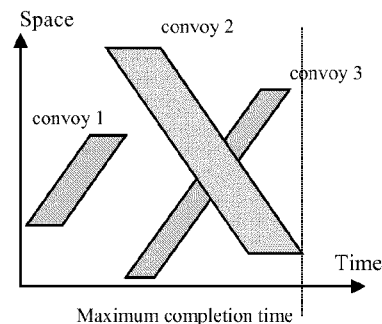


Figure 4: De-conflicting multiple convoys.

For the purpose of illustration we shall consider three convoys being moved along a single route. The overlapping of the time space occupancies associated with convoys 2 and 3 clearly indicates that these two convoys conflict en route. In this simple case, with a single route and a small number of convoys, the conflict can easily be resolved by sliding the time space occupancies of the convoys until there is no overlap. However, for realistic scenarios where there are large numbers of convoys and multiple routes such an approach is no longer practical. In fact, representing such situations by a simple graphic, as in Figure 4, is generally no longer an option.

The graphical approach illustrated in Figure 4 can, however, be generalised and this leads to the approach described in this paper.

We refer to the area of the overlap of the time space occupancies of conflicting convoys as the **size of the conflict**. De-conflicting two convoys corresponds to reducing the size of the conflict to zero. Hence instead of attempting to obtain a valid movement we relax the conflict prevention constraints by replacing them with an objective of minimising the size of any conflicts. Clearly optimal solutions with respect to this new objective will be valid movements. However, we wish to simultaneously minimise the overall completion time and the size of any conflicts. Hence we must optimise with respect to some function of the two objectives.

Whilst it remains difficult to find solutions that are optimal with respect to this relaxed problem, the relaxed problem has a particular structure that means it is relatively straightforward to find near optimal solutions to the relaxed problem. The relaxed problem is formulated in such a manner that the overall completion time of the relaxed problem is a **lower bound** of the minimal overall completion time of the original problem. In other words, the overall completion time of the relaxed problem is guaranteed to be no greater than the minimal overall completion time of the original problem.

The near optimal solutions to the relaxed correspond to movements with small numbers of conflicts that can easily be resolved by simple heuristics. The resulting valid movements will tend to have near minimal overall completion times.

In particular, we define our Lagrangian dual function, with respect to some Lagrange multipliers as the overall completion time of the *shortest paths* movement over a time-space network with a modified cost function minus penalty terms for the any conflicts in the *shortest paths* movement.

Each node in the time-space network has a Lagrange multiplier associated with it and the modifications to the cost function of the time-space network are in proportion to the magnitude of associated Lagrange multipliers. To be specific for each edge in the time-space network we add to its original cost the average value of the Lagrange multipliers associated with the incident nodes. The *shortest paths* movement is then generated over the cost-modified time-space network. A **penalty term** is defined, for each node in the space-time network, as the product of the node's Lagrangian multiplier and the total magnitude of conflicts at the node in the *shortest paths* movement obtained for the given Lagrange multipliers. Clearly if there are no conflicts the penalty term is zero.

The resultant Lagrangian dual function can be shown to always be a lower bound. Hence, the Lagrangian dual problem is then to find a set of Lagrange multipliers that maximise the value of the Lagrangian dual function, that is, the lower bound. The greater the lower bound is the tighter it is. The multipliers are updated by a subgradient optimisation procedure that is guaranteed, at each iteration, to move closer to the Lagrange multipliers corresponding to the maximal value of the dual function.

By maximising the Lagrangian dual function we are minimising the penalty terms. Hence the magnitude of the conflicts in the corresponding *shortest paths* movement are minimised.

Employing a modified version of Dijkstra's shortest path algorithm accelerates the calculation of the Lagrangian dual function.

6.1 Benefits of relaxation methods

Relaxation methods, as described, coupled with other heuristic provide not only a high quality and de-conflicted movement but they also provide a measure of its quality with respect to the optimal movement, via the lower bound. This provides added value to the movement produced in that there is a measure of how much scope there is for further improvement in the planned movement. Hence, the commander is provided with a degree of confidence in the planned movement.

The combination of rapid planning and a measure of confidence is a feature that is not generally shared by the majority of automated decision aids. Moreover, this is combined approach is equally applicable to a wide range of military applications.

7 The Planning Tool

A prototype planning tool has been developed based on the techniques described above and implemented on a standard PC platform. The planning tool provides the user with the capability to develop optimised movements for various scenarios and to visualise the solutions.

The planning tool allows the user to perform three main functions:

- to iteratively generate a sequence of valid movements of increasing quality and to monitor the progress of this improvement measured in terms of their convergence towards the optimal;
- to stop the technique on any iteration and view the movements of all or any subset of the convoys obtained, and
- to configure the software to tune the algorithms so that convergence is as rapid as possible.

7.1 Planning tool capability

The planning tool offers the capability of

- rapid and automated planning;
- the investigation of “what if” scenarios; and
- rapid re-planning.

7.2 Planning tool functionality

The planning tool is PC based; is able to run on a standard laptop; and provides

- a graphical interface to the planning tool; and
- a graphical tool for visualising and interrogating the obtained movements.

In order to plan a movement it is assumed that the user has available a vectorised description of the route network as well as a data file describing each of the convoys; their objectives and constraints in terms of their origin, earliest ready time, destination and any deadline. These data files form the input to the planning tool. It is assumed that these data files have been obtained from other tools. Given the necessary data files the user is able to load the scenario and begin the planning algorithm.

Generally the first iteration of the planning algorithm will result in a valid movement which is within 10% (or better) of the optimal.

Once a valid movement has been obtained the planning tool provides the user with the ability to *playback* the generated movements on a graphical display. In *playback* convoys are represented as “worms” which progress over a representation of the route network.

The planning tool provides the user with the ability to playback

- movements in step mode or play mode;
- movements forwards and backwards via a slide control; and
- subsets of movements.

All functionality is available via menus, dialog boxes and easy to use controls. A detailed description of the functionality of the planning tool can be found in [13].

7.3 Results obtained

The planning tool was evaluated on a number of realistic scenarios based on the UK MoD’s Scenario Advisory Group (SAG) settings.

Data sets	No. of nodes	No. of links	No. of convoys
P1	160	212	17
P2	530	724	25
Q1	932	2,482	166
Q2	1,145	3,058	333
Q3	7,232	15,496	1,817

Table 1: The test data sets.

The data sets used are summarised in Table 1. For all data sets, bar Q3, the planning tool is able to obtain movements that are within a few percent of optimal, or better, in the order of a few seconds to a few tens of seconds. In the case of data set Q3 tens of minutes are required to obtain a valid movement that is within a few percent of optimal. However, bearing in mind the size of data set Q3 even this performance is remarkable and of significant operational benefit.

7.4 Benefits of the planning tool

Such a planning tool, based on a combination of relaxation and heuristic based optimisation methods, reduces the effort required to plan movements from the order of man weeks to minutes of computing time. The speed of the planning tool also allows time for rapid replanning and the investigation of a number of “what if” scenarios.

Such a tool will enable military staffs to complete their movement plans far quicker than they can at present. This would lead to an

increase in the overall speed and tempo of operations. Such a tool would also enable staffs to quickly amend their plans if required. Once again this would serve to maintain a high operational tempo.

Our aim is to incorporate this planning tool into the British Army Battlespace Digitization Programme. The benefits of such a planning tool include

- automating the planning of large movements of military convoys, to be specific the automation of movement de-confliction; and
- the ability to visualise and interrogate the movements generated.

The automation of the planning process will result in benefits to the commander and his staffs of

- an increase in the speed of processing data;
- a reduction in the workload and stress of staffs freeing them for other roles and functions;
- the ability to cope with the highly complex scenarios associated with the modern battlespace with a greater level of accuracy and effectiveness; and
- the capability to rapidly re-plan when the original movement has been disrupted by third party action.

All of which leads to an increase in the speed and tempo of operations, which in turn enables the commander to get inside the opposing forces decision making cycle.

8 Planning Under Uncertainty

Optimal movements by definition attempt to minimise the planned delays on route. Such an approach will result in movements where once a convoy has cleared a junction the plan will specify that the next convoy will go through immediately. Of course such a plan leaves no margin for error. Simple experiments demonstrate that by introducing only small delays into an optimised movement rapidly leads to gridlock.

Therefore what we require are movements that are both optimised and robust. A movement is **robust** if it minimises the cost of disruption and re-planning if things do not go to plan. Simple mechanisms for producing robust movements are to introduce minimum inter-convoy spacings

or to artificially extend the convoy's time window in front and behind the convoy and route these extended virtual convoys. In the latter case this means that the true convoy can lie at any point within the virtual convoy during the plan's execution without disrupting the movements of other convoys. Inter-convoy spacings are already specified by many NATO nations when planning the movements of their convoys.

However, current research is investigating whether more sophisticated delay models and methods for planning in the presence of uncertainty will result in better plans in terms of their quality and robustness.

9 Other Applications

It has already been stated that constrained optimisation problems lie at the heart of many aspects of military decision making. Moreover the combination of techniques described in this paper are sufficiently generic that they can be applied to many of the constrained optimisation problems encountered in military decision making.

Therefore in this section we briefly review four further applications, of military relevance, where these techniques are either applicable or have already been applied by the Pattern and Information Processing group at DERA Malvern. For a further discussion of the construction of optimisation models from military applications, and methods used to solve them, the interested reader is referred to [15].

9.1 Depot outloading

One of the fundamental logistics roles of an armed force is the movement of men and equipments between storage locations and (sea and air) ports of embarkation coupled with the movement of men and equipments between ports of disembarkation and the operational theatre. Such movements are generally very large and require large amounts of planning in order to ensure all men and equipments are in the correct location at the correct time and that the appropriate logistical infrastructure is also available in the correct location at the correct time. We refer to this as **depot outloading**.

Not surprisingly depot outloading is a constrained optimisation problem. There are two objectives that can be considered in the depot outloading problem: either

- Outload a given number of men and equipments as quickly as possible; or

- For a given a deadline, outload as many men and equipments as possible by the deadline?

9.2 Earth observing satellites

Observation satellites have a limited window of opportunity for imaging or taking measurements of a given target area, dictated by orbit considerations. In low Earth orbit (typically 400 to 1200 km altitude) a ground object will be in view for a few minutes at most. Depending on the mode of operation of the satellite, the data taking window may range from a few minutes down to only a fraction of a second.

The scheduling problem then is one of achieving the maximum efficiency of use of a satellite. Traditionally this has been achieved by teams of ground planners who write, check and recheck procedures.

An initial feasibility study [4,5] has already demonstrated, for a simplified model of the satellite and its environment, that optimised taskings can be obtained in the lead times encountered in practice. A demonstration graphical planning tool has been developed.

9.3 Frequency assignment

Good communications are at the heart of successful military operations. The scope of modern radio communications technology is so attractive that ever more data is being exchanged on the battlefield, further down the command structure. But there is an overriding difficulty – the electromagnetic spectrum is physically limited, so congestion results. Bandwidth is becoming every bit as precious as fuel or ammunition.

Not surprisingly, the assignment of radio frequencies to transmitters under the constraints of bandwidth and interference described in the previous paragraph is a constrained optimisation problem with applications for cellular networks for mobile phones as well as the assignment of frequencies to networks of mobile transmitters in military operations. The application of heuristic based optimisation techniques to the assignment of radio frequencies is described in [16].

9.4 Collection management

Collection management, in the land domain, hinges on the ability of the military planner to satisfy a wide variety of requests for information (RFIs) each with a priority value associated to it. These RFIs must be satisfied by making an efficient utilisation of one or more of a varied array of assets. These assets include surveillance

sources, such as ISTAR, satellites and various agencies, along with a potentially large array of reconnaissance sources, such as manned and unmanned aircraft, plus ‘spot’ modes on some surveillance sources. Adding to the complexity of the planning problem is the fact that not all the collection assets are suitable for dealing with all RFIs and some RFIs may require more than one asset to satisfy. Furthermore the RFIs come with time windows during which they are to be answered.

This all leads to a complex and highly constrained scheduling problem, which is discussed in greater detail in [17]. Whilst the constrained optimisation problem at the heart of collection management is extremely challenging, the techniques described in this paper offer the potential to automate many aspects of collection management and to further reduce the workload and stresses imposed on the military commander and their staffs.

10 Conclusions

The principal message of this paper is that the combination of relaxation and heuristic based optimisation techniques provide a powerful set of tools for the automation of many aspects of the military decision process. Thus reducing the workload and stress of military staffs releasing them to concentrate on more strategic level planning.

A planning tool based upon or incorporating optimisation methods has been shown to reduce the effort required for planning, in the case of convoy planning the effort was reduced from the order of man weeks to minutes of computing time on a laptop.

An operational planning tool based on the concepts described in this paper would provide the commander and his staffs with the ability to provide high level outlines of a planned movement and leave the detailed planning to the tool. The benefits of automating the detailed planning in this manner include

- a reduced workload;
- reduced stress;
- supporting an increase in the speed and tempo of operations;
- the rapid generation of alternative plans; and
- the generation of new plans when the original plan has been disrupted by enemy action.

The speed of the planning tool also provides the commander and his staffs with the opportunity to explore a number of “what-if” scenarios. This is clearly not an option when the planning of a movement requires a significant effort on the part of the commander and his staffs.

Acknowledgements

The UK MoD Corporate Research Programme, TG10 RO4, funded the work described in this paper in its entirety.

The author would like to thank Major Ian Buchanan for helping to set this work in the full military context.

11 References

1. P. Chardaire, G. P. McKeown, S. A. Harrison and S. B. Richardson. Solving a Time-Space Formulation for the Convoy Movement Problem. *Operations Research* (submitted 1999).
2. K. Chih, M. P. Bodden, M. A. Hornung and A. L. Kornhauser. Routing and Inventory Logistics System: A Heuristic Model for Optimally Managing Intermodal Double-Stack Trains. *Journal of Transportation Research Forum* **31**:56 - 62, 1990.
3. M. Florian, G. Bushell and J. Ferland. The Engine Scheduling Problem in a Rail Network. *INFOR* **14**:121 - 138, 1976.
4. S. A. Harrison. *Task Scheduling for Satellite Based Imagery - An Initial Feasibility Study*. DERA Report DERA/S&P/SPI/TR990673, February 2000.
5. S. A. Harrison, M. E. Price and M. S. Philpott. Task Scheduling for Satellite Based Imagery. *Proceedings of the 18th Workshop of the UK Planning and Scheduling Special Interest Group (PLANSIG-99)*, pages 64 - 78, University of Salford, UK, December 1999.
6. M. Held and R. M. Karp. The Travelling Salesman Problem and Minimum Spanning Trees. *Operations Research* **18**:1138 - 1162, 1970.
7. E. Iakovou, C. Douligeris, H. Li and L. Yudhbir. A Maritime Global Route Planning Model for Hazardous Materials. *Transportation Science* **33**(1):34 - 48, 1999.
8. O. K. Kwon, C. D. Martland and J. M. Sussman. Routing and Scheduling Temporal and Heterogeneous Freightcar Traffic on Rail Networks. *Transportation Research, Part E: Logistics and Transportation Review* **34**(2):101 - 115, 1998.
9. Y. N. Lee, G. P. McKeown and V. J. Rayward-Smith. The Convoy Movement Problem With Initial Delays, in V. J. Rayward-Smith, C. Reeves and G. D. Smith (editors) *Modern Heuristic Search Methods*, John Wiley, pp. 215 - 236, 1996.
10. A. Martelli. An Application of Heuristic Search Methods to Edge and Contour Detection. *CACM* **19**:73 - 83, 1976.
11. A. Martelli. On the Complexity of Admissible Search Algorithms. *Artificial Intelligence* **8**:1 - 13, 1977.
12. N. Nilsson. *Problem Solving Methods in Artificial Intelligence*, McGraw Hill, 1971.
13. S. B. Richardson. *User guide for the BSS convoy movement optimisation tool*. DERA Report DERA/LS(LSB2)/BSS(SCEN)/CMP/1. March 1999.
14. N. Z. Shor. Generalisations of Gradient Descent Methods for Nonsmooth Functions and their Applications to Mathematical Programming. *Econ. Math. Methods* **12**:337 - 356, 1976.
15. C. L. West. *Combinatorial Algorithms for Military Applications (CALMA)*. DERA Report DRA/CIS(SE1)/608/08/07/Final_1, DERA, 1996.
16. M. L. Williams. Making best use of the airways - an important requirement for military communications. *Electronics and Communications Engineering Journal* (to appear) 2000.
17. M. L. Williams. *Scheduling for Collection Management*. DERA Report DERA/S&P/SPI/TR000278/1.0
18. The Studies Assumptions Group: Scenarios and Assumptions for Studies, Interim SDR version issue 3, D/DFD/10/2/3.